Tracking sedimentation from the historic 2011 Mississippi River Flood in the deltaic wetlands of Louisiana, USA

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ABSTRACT

Management and restoration of the Mississippi River Deltaic plain and associated wetlands requires a quantitative understanding of sediment delivery during large flood events, past and present. Here, we investigate the sedimentary fingerprint of the 2011 Mississippi River flood across a broad expanse of the Louisiana coast (Atchafalaya Delta, Terrebonne, Barataria and Mississippi River Delta basins) to assess spatial patterns of sedimentation and to identify key indicators of sediment provenance. The sediment deposited in wetlands during the 2011 flood event was distinguished from earlier deposits based on biological characteristics, primarily absence of plant roots and increased presence of centric (planktonic) diatoms indicative of riverine origin. By comparison, the lithological (bulk density, organic matter content and grain size) and chemical (stable carbon isotopes of bulk organic matter) properties of flood sediments were nearly identical to the underlying deposit. Flood sediment deposition was greatest in wetlands near the Atchafalaya and Mississippi Rivers and accounted for a substantial portion (35 to 88%) of the annual accretion measured at nearby monitoring stations. The amount of sediment delivered to those basins (1.1 to 1.6 g cm^2) was comparable to that reported previously for hurricane sedimentation along the Louisiana coast (0.8 to 2.1 g cm^2). Our findings not only provide insight into how large-scale river floods influence wetland sedimentation, they lay the groundwork for identifying previous flood events in the stratigraphic record.

INTRODUCTION

The rapid disappearance of the Mississippi River deltaic wetlands is in part a consequence of hydrologic alteration (DeLaune et al., 1989; Reed, 1992; Turner, 1997), which has resulted in decreased delivery of sediment and freshwater (Day et al., 2000; Blum and Roberts, 2009). Wetlands evade persistent inundation when increases in surface elevation offset relative sea-level rise (DeLaune et al., 1983; Day et al., 2000). Surface elevation gains result from the accumulation of organic material from wetland vegetation and mineral sediment deposition (Reed, 1995; Cahoon, 2006). While numerous studies have examined the effect of hurricanes on wetland sedimentation (Turner et al., 2006; McKee and Cherry, 2009), less is known about the efficacy of rivers to deliver sediment directly to these wetlands during high flow events. The 2011 Mississippi River flood provided an opportunity to address this imbalance.

Enhanced snowmelt and a series of storms in Spring 2011 generated one of the largest floods on the Mississippi River since 1927 (National Weather Service, 2011). To alleviate stress on the river control system downstream, the Morganza Spillway was opened on May 14, 2011. As diverted waters (maximum of 3500 $m^3 s^{-1}$) surged down the Morganza floodway to inundate the wetlands of the Atchafalaya floodplain, high flows (~20,000 $m^3 s^{-1}$) were sustained within the main Mississippi channel from May 14–31, 2011 (Louisiana Water Science Center, 2012). Here, we report spatial variation in wetland sediment accumulation across the Atchafalaya Delta (AD), Terrebonne (TB), Barataria (BA) and Mississippi River (Birdsfoot) Delta (MRD) basins and provide the first estimate of the volume of sediment delivered to deltaic wetlands during a historical flood event. In addition, we reveal a 'flood' indicator that may be used to identify similar events in the stratigraphic record.

POST-FLOOD SURVEY

In late June 2011, we accessed 45 sites across wetlands in the four basins and retrieved a total of 225 shallow sediment cores (5 cores/site). At each site, the flood sediment was visually distinguished from underlying sediment by its distinct color and texture (Fig. 1). The lack of live plant roots in this layer compared to underlying rooted strata suggested that deposition occurred very recently (within 1 - 2 months of sampling), which aligns with the time frame of the flood (GSA data repository).

FLOOD SEDIMENT CHARACTERISTICS

Physical and Chemical Properties of Flood Sediments

Flood sediment depth and accumulation varied significantly among basins, irrespective of the sample site elevation (GSA data repository). The thickness of the flood sediment layer varied from 0.0 to 8.3 cm, with a coast-wide average of 1.5 cm. We calculated average accumulation at each site using mean depth measurements of the flood sediment and its bulk density. The greatest accumulation occurred in the AD basin (1.6 ± 1.0 g cm^{-2}), while an intermediate amount was observed in the MRD basin (1.1 ± 0.8 g cm^{-2}). Minor accumulation occurred in sites in the TB (0.4 ± 0.2 g cm^{-2}) and BA (0.3 ± 0.2 g cm^{-2}) basins, which were negligibly impacted by the flood due to their remoteness to river mouths (Fig. 2).

There were no discernible differences in the lithological and chemical characteristics between flood and underlying sediments across basins (Fig. 2). The flood sediment contained clay to coarse silt-sized particles (median grain size: 13.4 ± 1.6 μm) with an organic matter content of 9.8 ± 1.1% and bulk density of 0.6 ± 0.1 g cm^{-3}. There were no systematic differences among basins based on lithological characteristics. However, $\delta^{13}C$ of the AD and MRD (–27.0 ± 0.4 ‰ and –24.7 ± 0.5 ‰, respectively) differed significantly from that in the BA and TB (–18.6 ± 0.6 ‰ and –19.1 ± 0.5 ‰, respectively) basins. The $\delta^{13}C$ of the AD and MRD basins are within the range of values for a freshwater source (–25 ‰ <$\delta^{13}C$ < –28 ‰), which suggests a terrestrial provenance for flood sediments; if sediments had a marine source, we would expect a shift in $\delta^{13}C$ in the AD and MRD toward values of marine particulate organic matter (–18 ‰ < $\delta^{13}C$ < –24 ‰) (Lamb et al., 2006; Bianchi et al., 2011). The isotopic variations among basins are also consistent with their dominant vegetation type; the AD and MRD sampling sites primarily contained C_3 freshwater vegetation (–22.8 ‰ <$\delta^{13}C$ < –30.5 ‰), while the TB and BA sites were dominated by C_4 *Spartina alterniflora* (–12.1 ‰ <$\delta^{13}C$ < –13.6 ‰) (Chmura et al., 1987).

Biological Characteristics of Flood Sediments

Flood diatom assemblages differed from those of pre-flood sediment (GSA Data repository) and provide insight into the mode of sediment deposition and its provenance. Diatoms are unicellular algae encased in a silicic cell wall, which are found in nearly every wet or aquatic environment (Round et al., 1990). Diatoms respond to a number of environmental factors (Hustedt, 1953) and have been used to infer long-term variations in water level and flooding in inland floodplain lakes and rivers (Engle and Melack, 1993; Van der Grinten et al., 2008), but have not been used to examine regional flood events. Flood diatom assemblages displayed a marked increase in the proportion of centric (planktonic) taxa relative to pennate (benthic) forms (Fig. 2). The centric to pennate ratio was greater in the AD and MRD basins (127% increase) compared to the BA and TB basins (23% increase). Centric forms typically float freely within the water column, while pennate forms, which live attached to vegetation and substrate, dominate the wetland surface (Denys, 1991/1992; Vos and Dewolf, 1993). Greater inundation and flow over the surface of deltaic wetlands caused by the 2011 flood increased connectivity between the river and wetlands. The increased connection produced a subsequent shift in diatom habitat that promoted the proliferation of centric, riverine taxa (e.g., Weilhoefer et al., 2008), which were increasingly incorporated into flood sediment as it settled out of suspension.

There was also a shift in the benthic population of AD and MRD flood deposits. *Nitzschia* spp. replaced *Navicula* spp. in dominance, which suggests a greater degree of turbidity and suspended sediment in waters over the inundated wetland surface (Bahls, 1993). The appearance of the tychoplanktonic form *Staurosira construens* in flood sediments of the MRD and its relative absence in those of the AD may reflect the comparatively high flows sustained in the MRD during the flood (Stevenson, 1983; Peterson, 1986). Flood assemblages shared a striking similarity to species composition of overbank deposits from floods along the Red River (a tributary of the Atchafalaya River; Medioli and Brooks, 2003) and contained a high number of eutrophic freshwater to brackish diatom species (e.g., *Cyclostephanos invisitatus, Cyclotella cryptica* and *Cyclotella meneghiniana*; Vos and Dewolf, 1993; Van Dam et al., 1994), supporting the inference from $\delta^{13}C$ values of a riverine provenance of sediments.

SIGNIFICANCE OF THE 2011 FLOOD

We calculate the mean 2011 flood accumulation for all four basins to be 0.9 ± 0.2 g cm^{-2}, which accounts for 56% of annual accumulation recorded at Coastal Reference Monitoring System (CRMS) sites located adjacent to our sampling points (data from 2007 to present; Table 1). Flood deposition in the AD (1.6 ± 1.0 g cm^{-2}) accounted for 85% of annual accretion recorded at the monitoring sites, yet only 44% in the MRD (1.1 ± 1.0 g cm^{-2}). Consistent with spatial patterns of deposition, the TB (0.4 ± 0.2 g cm^{-2}) and BA (0.3 ± 0.2 g cm^{-2}) basins showed less contribution to annual accretion during the same time period (37% in both basins). The Mississippi River channel received over five times greater volume of floodwater than the Atchafalaya (U.S. Army Core of Engineers, 2011), although less sedimentation occurred in the MRD wetlands. Falcini et al. (*in press*) suggest the relatively low sedimentation in the MRD may be due to hydrodynamic characteristics of the sediment plume produced by the Mississippi, where the focused, jet-like plume delivered sediments far into the Gulf of Mexico. Greater accretion in the AD may be due to overbank flow caused by the opening of flood diversions and plume-derived sedimentation from the mouth of the Atchafalaya River, which was characterized by a wide, diffuse plume that inundated a greater area of wetland and was contained within coastal currents (Falcini et al., *in press*).

A comparison of our data with hurricane-induced sedimentation estimates provides further insight into the relative importance of the 2011 flood event. Following the 2005 landfall of hurricanes Katrina and Rita, Turner et al. (2006) reported a mean accumulation of 2.2 g cm^{-2} in the Chenier and Deltaic Plains for the two events combined. Turner et al. (2006) estimated that these hurricanes delivered 131×10^6 MT of sediment to the Louisiana coast, a value 5.5 times greater than their estimate of annual inputs of river sediment by overbank flooding and crevassing (pre-levee construction) of 6.6×10^6 MT. Törnqvist et al. (2007) calculated that annual delivery of sediment to the Wax Lake Delta alone is $4.3–5.8 \times 10^6$ MT yr^{-1} and emphasized that the hurricane sedimentation estimates were exaggerated because the widespread erosion resulting from the hurricanes (Barras, 2007) was not considered. To compare these estimates with the total volume of sediment deposited in deltaic wetlands during the 2011 flood, we multiplied the average basin accumulation by 2010 land cover assessments of 593.9 and 357.50 km^2 in AD and MRD (Couvillion et al., 2011). The 95% Confidence Intervals calculated for the AD and MRD basins were $2.8–14.7 \times 10^6$ and $0.6–7.2 \times 10^6$ MT, respectively, with negligible volumes for the TB and BA basins (Table 1). We note that such calculations may over- or underestimate the landscape-level deposition volume due to uncertainties in local spatial variation and habitat differences influencing sediment trapping (see GSA data repository for details). Flood sediments also may be reworked after deposition (e.g., Williams, 2011), or conversely, sediment deposited in near shore environments during a flood may be transported onshore to wetlands from tidal action or storms. However, the potential for preservation should be greater in the sedimentary record of subsiding coastlines (Dura et al., 2011), such as Mississippi River Deltaic plain. The ultimate influence of the 2011 flood on vertical land building will be determined by rates of accretion in relation to subsidence occurring in each basin. Long-term observations are necessary to fully evaluate the overall role of this and other large-scale floods in wetland maintenance, either by long-term monitoring of CRMS sites sampled during the flood or by identification of past events in the stratigraphic record.

CONCLUDING REMARKS

The 2011 Mississippi River flood carried large quantities of sediment to the declining wetlands of Louisiana in amounts that are significant in comparison to long-term accretion rates and estimates of hurricane deposition. Our results show how riverine sources bring considerable amounts of sediment to wetlands on river deltas during large floods, yet are ineffective at delivering sediment to areas far removed from river channels. Given the high current velocities required to entrain consolidated mud of the composition observed (> 1 m/s; Raudkivi, 1998), it is unlikely that wetland deposits were eroded from elsewhere on the Delta. Hurricanes rework river-derived sediment onto wetlands, while the flood deposition we report is a net addition of sediment rather than a redistribution.

This study describes a unique set of characteristics of flood sediments to identify former pulses of inorganic sediment found in deltaic wetland stratigraphy: 1) diatom assemblages that increase in centric taxa and *Nitzschia* species, both of which are related to greater inundation or flow over the wetland surface; 2) indication of a freshwater/riverine provenance of sediment supported by salinity preference of diatoms and carbon isotopic composition; and 3) little change in lithological characteristics compared to pre-flood sediment. These three characteristics differ from those produced by storm surges. Hurricane deposits along the Gulf Coast have been characterized predominantly by their coarse grain size and a marine component to their provenance (Parsons, 1998; Williams, 2009; Hawkes and Horton, 2012). The flood signature we describe may aid in future investigations of the relative contributions of floods and hurricanes to delta dynamics.

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FIGURE CAPTIONS

Figure 1. Recent sedimentation measured using a “mini-McCaulay” corer during the wetlands survey. Flood sediments (red bracket) were distinguished by an absence of live root ingrowth, an

unconsolidated consistency, and a different color compared to the underlying, pre-flood sediments (blue bracket).

Figure 2. Flood sediment accumulation and its physical, chemical, and biological characteristics. a. Location of sampling points and the depth of flood sediment measured at each site. Coastal basins are separated by black line and the area over which volume estimates were calculated in the Atchafalaya Delta and Mississippi River Delta basins is shaded dark gray. b. Average accumulation (g cm^{-2}) measured at each site. Flood (colored diamond) and pre-flood (open triangle) of bulk density (c), organic matter content (d), stable carbon isotopes (e), and centric:pennate (C:P) ratio of diatoms and its percent change (from pre-flood to flood) (f).

[1] GSA Data Repository item 2013xxx, details of site selection and sampling, methods, sediment volume calculations, statistical analyses, and raw data of physical, chemical, and biological sediment analyses, is available online at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

TABLE 1. COMPARISON OF FLOOD SEDIMENTATION MEASUREMENTS TO ANNUAL ACCRETION RATES AND HURRICANE SEDIMENTATION ESTIMATES

	Mean accumulation (g cm^{-2})*			Volume (10^{6} metric tons)	
Basin[†]	Flood (this study)	Annual (CRMS sites)[§]	Hurricane (Turner et al., 2006)	Flood (this study)[#]	Hurricane (Turner et al., 2006)**
AD	1.6 ± 1.0	1.8 ± 0.4	No data	2.8–14.7	No data
BA	0.3 ± 0.2	0.9 ± 0.6	2.1 ± 0.7	Not applicable	48.1
MRD	1.1 ± 0.8	2.6 ± 0.6	No data	0.6–7.2	No data
TB	0.4 ± 0.2	1.1± 0.5	0.8 ± 0.7	Not applicable	22.1
Coast-wide	0.9 ± 0.2	1.6 ± 0.3	2.2 ± 0.3	3.2–21.9	131

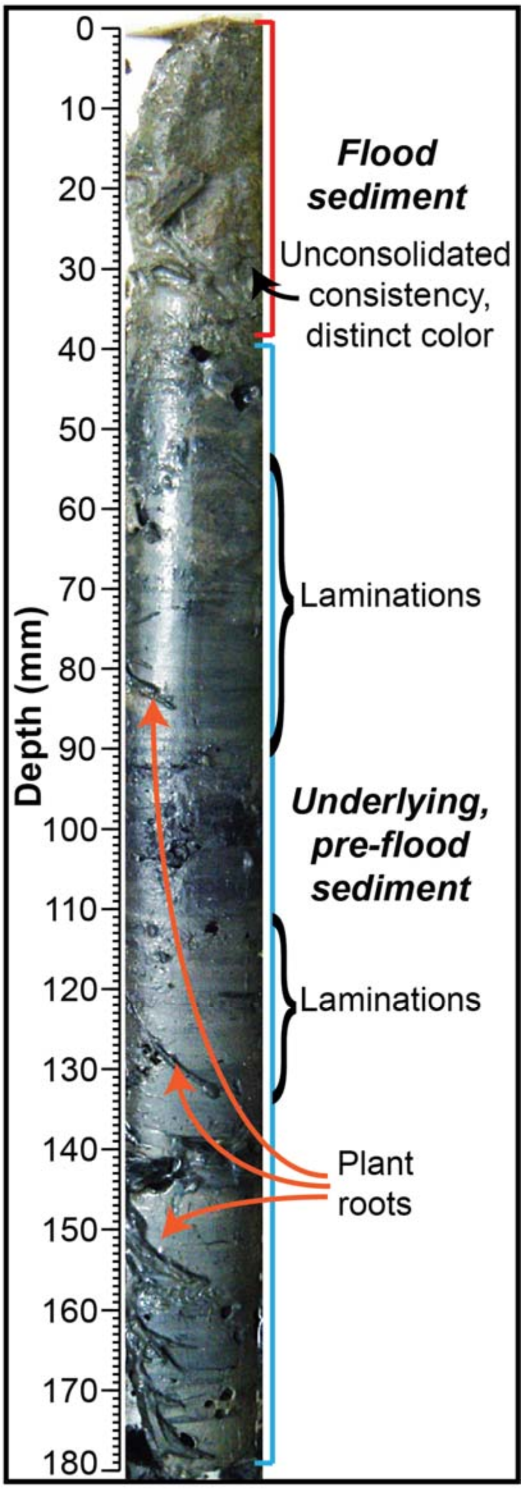
*Mean accumulation was determined by multiplying the depth of sediment layer by its bulk density, ± represents 1 standard error of the mean.

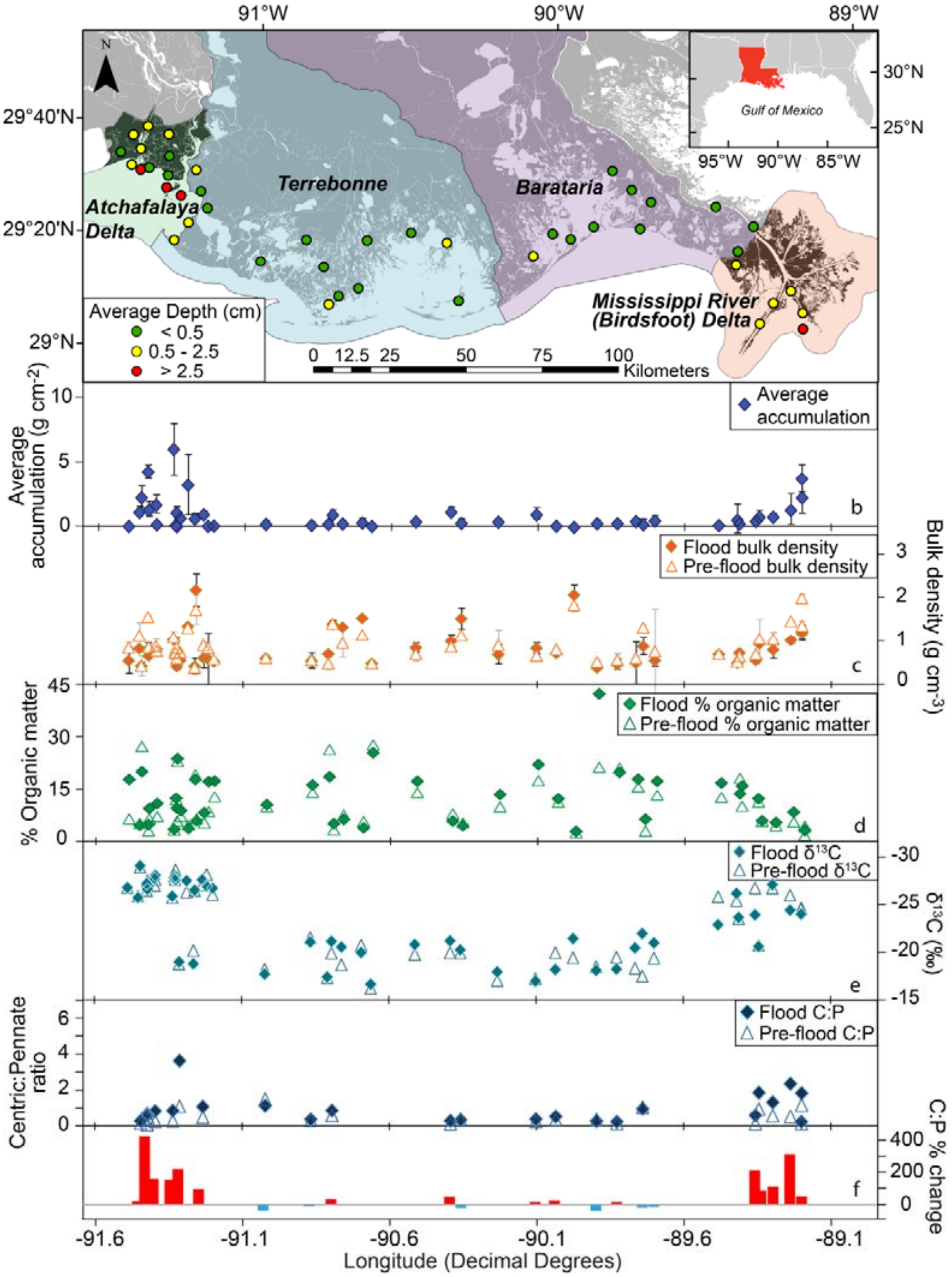
†AD =Atchafalaya Delta; BA = Barataria; MRD = Mississippi River Delta; TB = Terrebonne

§Coastal Reference Monitoring Sites.

#Volume estimates are reported as a 95% Confidence Interval range; no values are reported for the Terrebonne or Barataria basins because sampling coverage was insufficient to extrapolate basin-wide.

**Basin sediment volumes calculated using hurricane sediment depth and bulk density measurements from Turner et al., 2006 and 2004 land cover estimates (Couvillion et al., 2011); the coast-wide volume was calculated by Turner et al., 2006 for hurricane accumulation in all basins of the Louisiana Chenier and Deltaic plains.


Depth (mm)
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
Flood sediment
Unconsolidated consistency, distinct color
Laminations
Underlying, pre-flood sediment
Laminations
Plant roots


91°W
90°W
89°W
29°40'N
29°20'N
29°N
N
30°N
25°N
Gulf of Mexico
95°W
90°W
85°W
Terrebonne
Barataria
Atchafalaya Delta
Mississippi River (Birdsfoot) Delta
Average Depth (cm)
< 0.5
0.5 - 2.5
> 2.5
0
12.5
25
50
75
100
Kilometers
Average accumulation (g cm-2)
10
5
0
Average accumulation
b
Flood bulk density
Pre-flood bulk density
Bulk density (g cm-3)
3
2
1
0
c
% Organic matter
45
30
15
0
Flood % organic matter
Pre-flood % organic matter
d
Flood δ13C
Pre-flood δ13C
δ13C (‰)
-30
-25
-20
-15
e
Centric:Pennate ratio
6
4
2
0
Flood C:P
Pre-flood C:P
C:P % change
400
200
0
f
-91.6
-91.1
-90.6
-90.1
-89.6
-89.1
Longitude (Decimal Degrees)